THE METEOROLOGICAL ASPECTS OF ICE COVER ON THE GREAT LAKES*

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ABSTRACT

The formation and break-up of ice on the Great Lakes as observed by regular ice reconnaissance flights conducted by the Meteorological Service of Canada is discussed in terms of the meteorological parameters involved. Ice cover on the individual lakes over the past four years is correlated with the winter temperature regime and an index of the heat stored in each lake using the concept of cumulative degree-days of freezing and thawing. Subjective consideration is also given to the effect of other meteorological factors.

As a result of the study, graphs and regression equations have been developed as aids in the prediction of ice cover for the individual lakes. In addition, a comparison of the four years of observations with the 14-yr. period from 1949 to 1963 provides an indication of the average and extreme ice conditions that may be expected for each lake.

1. INTRODUCTION

Regular ice reconnaissance flights over the Great Lakes, excluding Lake Michigan, have been conducted by the Meteorological Service of Canada since 1960. (Archibald, Monsinger, Kilpatrick [1, 2, and 3]). While four years does not constitute a substantial length of record, ice on the lakes is of such importance to navigation, hydroelectric services, and meteorological forecasting that a preliminary assessment of the meteorological factors affecting ice cover on the Great Lakes appears justified.

A review of the literature reveals that since Fourier first developed the mathematical theory of heat conduction considerable progress has been made in correlating the increase in ice thickness to meteorological parameters (Calloway [6]). Some very elaborate empirical equations, such as those of Kolensnikov, have been developed that include most, if not all, of the meteorological factors significant to the formation and growth of ice. While underlining the complexity of the problem, the majority of these equations prove cumbersome in actual application.

2. METHOD

Basically, ice formation and dissipation may be considered as a function of (1) the severity of the winter, (2) the amount of heat stored in the water-body prior to the freezing season, and (3), in varying degrees of importance, a number of other meteorological parameters including cloud cover, radiation, wind, heat transfer, evaporation, and condensation.

DEGREE-DAY CONCEPT

The degree-day concept is a useful method for the direct accounting of the daily mean or maximum temperatures. This concept has been employed by a number of authors in the study of ice, and many ice-forecasting techniques depend upon it as a basic tool. (Lebedev [7], Lee and Simpson [8], Burbidge and Lauder [5], Markham [9]).

Although there are several definitions, the one most used in ice studies defines the freezing degree-day as the depression of the mean temperature by 1° F. below 32° F., for one day. Since both the duration of freezing temperatures and the magnitude of the depression below 32° are considered, the accumulated total of freezing degree-days proves a reliable measure of the severity of winter. The parallel concept of thawing degree-days provides a similar basis for break-up studies.

It is also recognized that the degree-day method not only provides a direct accounting of temperatures, but also an index of many of the meteorological factors dealt with in the more complex ice equations, which, in practice, are often too difficult to apply.

HEAT STORAGE

The amount of heat stored in a body of water depends chiefly on two variables: (1) the amount of heat made available for storage during spring, summer, and fall, and (2) the capacity of the individual lake for storing this heat.

In this particular study the number of thawing degree-days accumulated during each heating season was taken as an index of antecedent heating, and thus, as an index of the heat available for storage.

The capacity of the individual lake for heat storage is a function of the mean depth and is, therefore, fixed for each lake. For this reason each lake was treated separately.

3. PRACTICAL APPLICATION

The fundamental approach outlined above was used to assess the changes in ice cover on each of the Great Lakes

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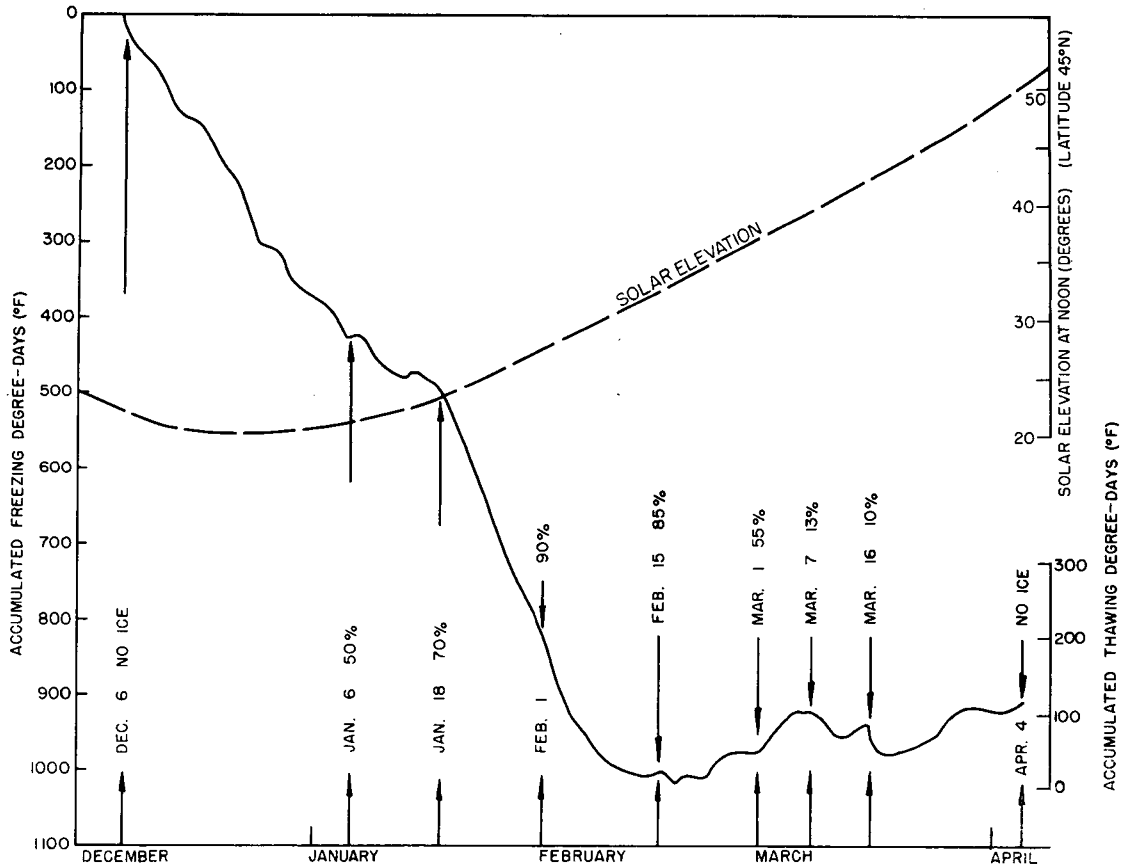

FIGURE 1.—Lake Erie ice cover (percent) winter of 1960–61 versus accumulated freezing and thawing degree-days at London, Ontario, and solar elevation at latitude 45° N.

as related to observed meteorological parameters. As a first step, the percentage of observed ice cover was correlated with the accumulated freezing degree-day data from a representative meteorological station. Secondly, the antecedent heating indices were calculated for each year under study. In addition further subjective investigations were made to assess the relative importance of other meteorological and limnological factors.

EXAMPLE: LAKE ERIE—WINTER 1960–61

As an example of the practical application of the method figure 1 was developed to illustrate the freezing and thawing regime of the winter of 1960–61 using accumulated degree-days at London, Ontario. The dates of the reconnaissance flights and the percentages of ice cover observed each time are noted and indicated by arrows.

It is evident that there is a good correlation between ice cover and degree-days up to mid-February, but after this time it appears that relatively few thawing degree-days are required to reduce the cover. Investigation revealed that ice cover diminishes with maximum daytime temperatures just above 32°F., even though mean temperatures remain below freezing. Further to this point, the superimposed graph of the solar angle in figure 1 suggests that this rapid decrease in cover is also associated with increased solar elevation, and thus, with increased incoming solar radiation, during the late winter. In addition, the intrusion of air masses with higher humidities in the early spring leads to condensation, and thus to another contribution to melting—the release of latent heat of condensation.

4. RESULTS

LAKE ERIE

The same procedure was followed for all four years of record to produce figure 2—a graph of ice cover on Lake Erie versus accumulated degree-days at London. A number of major characteristics become evident; some appear basic to the freezing and melting of all lakes; others are apparently associated with the fact that Erie, with a mean depth of 58 ft., is the shallowest of the Great Lakes.

—Lake Erie freezes quickly; 50 percent ice covered after only 300–400 freezing degree-days; 90–100 percent covered after 700.

—Erie clears rapidly; ice cover nil after 100–150 thawing degree-days.

—The assumption that antecedent heating is an index of heat stored in the lake appears justified. Erie froze

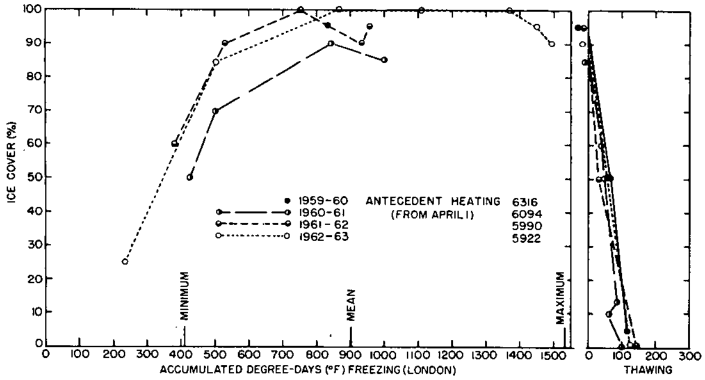

FIGURE 2.—Lake Erie ice cover (percent) versus accumulated freezing and thawing degree-days at London.

more rapidly in 1961–62 and 1962–63 after relatively cool summers with low antecedent heating terms.

—Following the pattern noted in 1960–61 the other years of record confirm that Lake Erie will freeze over completely and then show open water even while freezing degree-days are still accumulating. In the cases investigated these periods were in the latter half of the winter, and were preceded by several days with daytime temperatures above 32°.

To present the results of figure 2 in their proper perspective the degree-day climatology for London was investigated by machine methods for the 14-yr. period 1949–63. The average number of accumulated freezing degree-days was 901, the maximum 1528, and the minimum 410. These figures are plotted on figure 2 and by implication give an indication of the average and extreme ice conditions that may be expected.

Figure 3 was developed to illustrate further the degree-day data for the 14-yr. period. Included in the diagram are averages and extremes of the date of beginning of freezing, date of end of freezing, accumulated freezing degree-days, and antecedent heating terms. The straight line drawn from the average date of the beginning of freezing (November 29) to the average date of the end of freezing (March 17) at the average number of freezing degree-days (901) may be taken as the mean freezing line. The mean thawing line was drawn in a similar manner. The rectangle, then, encloses the meteorologically possible position for the apex of the freezing and thawing lines.

Transposing the means and extremes of the degree-day data from figure 3 to figure 2 will then indicate the means and extremes of ice cover that appear meteorologically possible in Lake Erie.

LAKE SUPERIOR

A similar investigation of ice on Lake Superior made use of temperature data from Lakehead Airport (Fort William and Port Arthur, Ontario). In contrast to Erie, Lake Superior is the deepest of the Great Lakes with an average depth of 487 ft. Figure 4 illustrates the relationship of Superior ice cover to Lakehead temperatures.

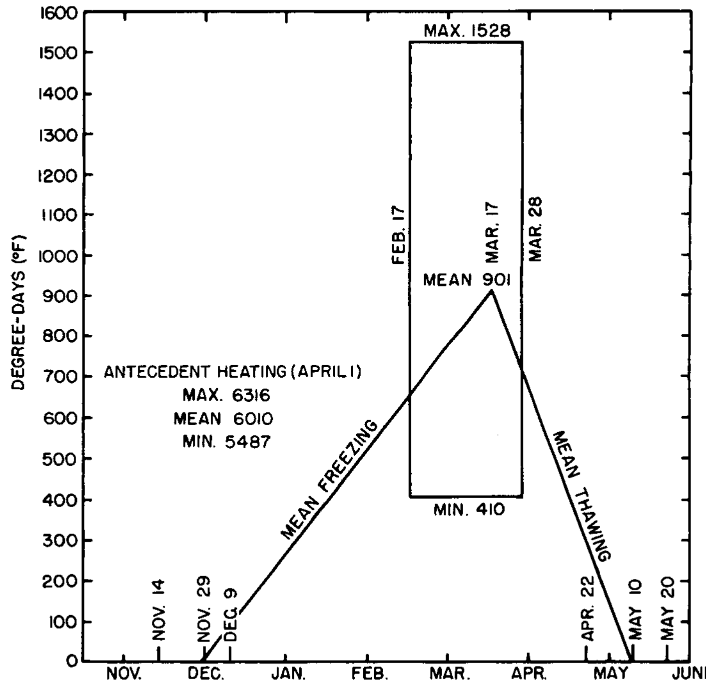

FIGURE 3.—Thawing and freezing degree-day climatology, London, means and extremes 1949–63.

Again, a number of distinctive features become apparent. As with Erie some appear basic to the freezing and melting of all lakes, others are characteristic of a deep lake.

—There is little ice cover on Lake Superior, other than in bays, until after an accumulation of 1000–1400 freezing degree-days. Thunder Bay and Whitefish Bay freeze over after 900 freezing degree-days.

—Superior, at times, becomes 90–100 percent ice covered but this requires an accumulation of 2000 freezing degree-days as compared to 700 for Erie. This is taken as a direct reflection of the heat storage capacity of the deeper lake.

—The antecedent heating term again appears to be a good index of stored heat. Superior froze over more rapidly and more completely during the winter of 1962–63 after the coolest summer of the four years under study (antecedent heating term 4017 as compared to about 4300 for the other years).

—Lake Superior will almost completely freeze over but then return to as much as 50 percent open water even while freezing degree-days are still accumulating. All the cases of reduced cover in figure 4 followed major storms. Besides the melting factors discussed under Lake Erie it may be postulated that wind and wave action broke up the thinner ice, compacted the remnants, and produced mixing that transported to the surface the warmer water usually stored at lower levels in the winter. A lake as deep as Superior has a very large capacity for heat storage and has, therefore, an almost unlimited supply of warmer water (38° F.).

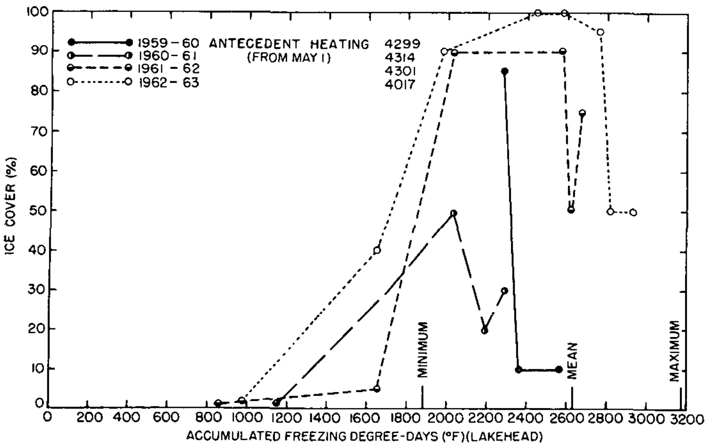

FIGURE 4.—Lake Superior ice cover (percent) versus accumulated freezing degree-days at Lakehead Airport, Ontario.

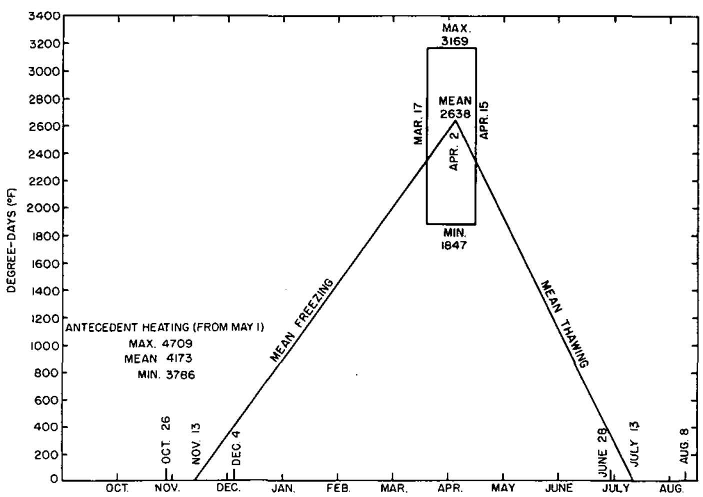

FIGURE 5.—Thawing and freezing degree-day climatology, Lakehead, means and extremes 1949–63.

To make the results of figure 4 more meaningful, the means and extremes of the degree-day data for Lakehead were computed and are presented in figure 5.

GEORGIAN BAY

Because of its obviously different ice characteristics Georgian Bay was treated separately from Lake Huron. The same procedures were used to develop figures 6 and 7 with Gore Bay on Manitoulin Island as the representative meteorological station.

Like Erie, Georgian Bay will freeze over completely during an average winter and will apparently become 80 percent ice-covered even during the mildest of winters. Unlike Erie, and more characteristic of the deeper lakes, the bay will go from nearly 100 percent covered to less than 50 percent even while mean temperatures remain below 32°.

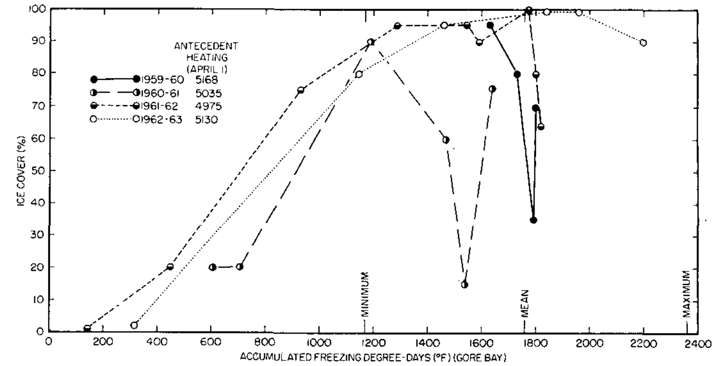

FIGURE 6.—Georgian Bay ice cover (percent) versus accumulated freezing degree-days at Gore Bay.

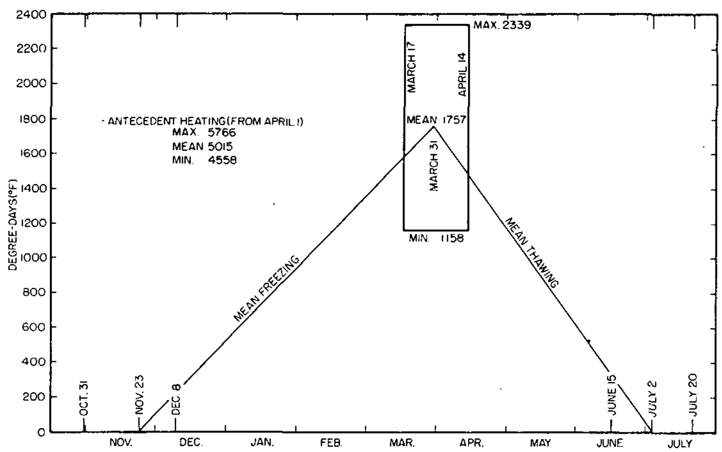

FIGURE 7.—Thawing and freezing degree-day climatology, Gore Bay, means and extremes, 1949–63.

LAKE HURON

Because of its north-south orientation it was difficult to find a single representative meteorological station for Lake Huron. By trial and error it was found that an average of temperature data from Gore Bay and London produced the best correlation with observed ice cover. The results are shown in figure 8.

Lake Huron, with a mean depth of 195 ft., exhibits characteristics of a deeper lake. Only during a very severe winter does it come close to freezing over, and, like Superior, ice cover is greatly reduced under wind and wave action.

LAKE ONTARIO

Ice cover on Lake Ontario was studied in relation to temperature data from Toronto, Ontario, as shown in figures 9 and 10. As the second deepest (mean depth 283 ft.), and the second most southerly, of the Great Lakes, Ontario experiences the least ice cover of all the lakes. In the four years of record, ice cover never exceeded 60 percent and, extrapolating from the temperature data in

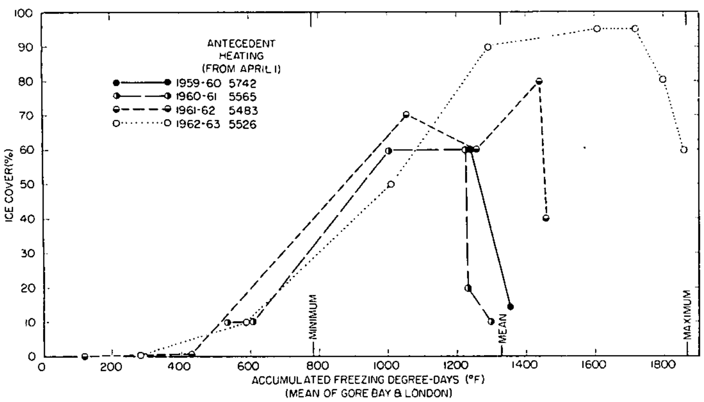

FIGURE 8.—Lake Huron ice cover (percent) versus the mean of accumulated freezing degree-days at Gore Bay and London.

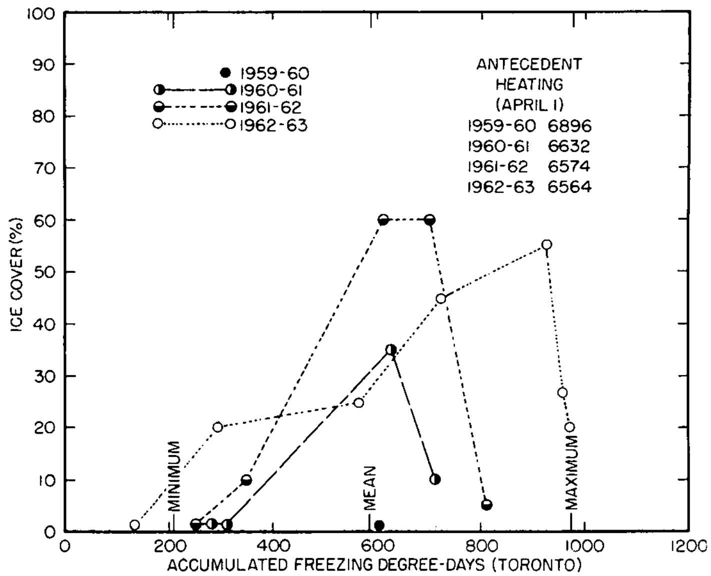

FIGURE 9.—Lake Ontario ice cover (percent) versus accumulated freezing degree-days at Toronto, Ontario.

figure 10, it appears unlikely that Ontario would ever freeze over.

Strong currents have also been suggested as contributing to the lack of ice on Lake Ontario, but on the basis of the little data available, the existence of such currents may well be questioned.

5. MULTIPLE REGRESSION EQUATIONS

The correlation of ice cover with accumulated freezing degree-days and antecedent heating was so consistent for all the lakes (figs. 2, 4, 6, 8, 9), that the results invited the application of a multiple regression equation of the form

$$Y=b_0+b_1X_1+b_2X_2$$

where Y=ice cover (percent); X_1=accumulated freezing degree-days; X_2=antecedent heating.

Fifty-six observations from first ice to maximum cover where used in the study. Standard tests, including the coefficients of multiple regression (R) and the standard errors (S), confirmed satisfactory statistical correlations. (N=number of observations.)

Lake Superior

$Y=117.3+.095X_1-.058X_2$ $R=.8768$
$S=15.6$ $N=10$ (1)

Lake Huron

$Y=178.8+.077X_1-.038X_2$ $R=.9535$
$S=8.9$ $N=12$ (2)

Georgian Bay

$Y=102.8+.065X_1-.022X_2$ $R=.9093$
$S=12.6$ $N=14$ (3)

Lake Erie

$Y=318.8+.102X_1-.050X_2$ $R=.8750$
$S=11.1$ $N=9$ (4)

Lake Ontario

$Y=281.2+.075X_1-.044X_2$ $R=.7911$
$S=11.0$ $N=11$ (5)

6. CONCLUSIONS

From a study of four years of ice observations on the

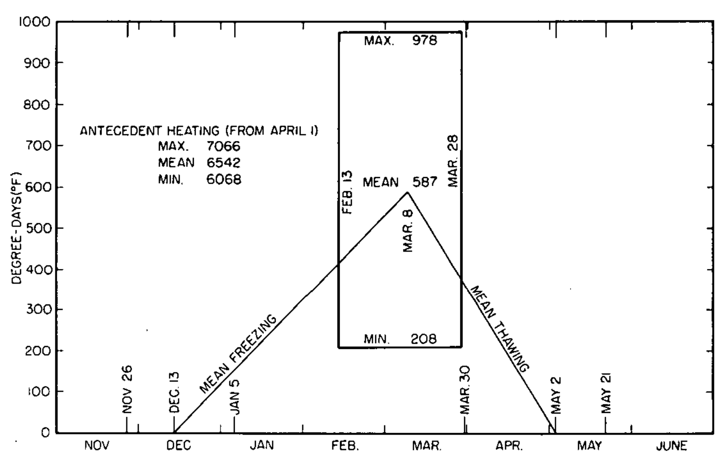

FIGURE 10.—Thawing and freezing degree-day climatology, Toronto, means and extremes 1949–63.

Great Lakes it is apparent that there is good correlation between ice cover on each lake and degree-day data as recorded at representative meteorological stations (figs. 2, 4, 6, 7, 9).

Degree-day data from a 14-yr. record were used to calculate averages and extremes for these stations (figs. 3, 5, 8, 10) and these may be used to indicate the meteorologically possible average and extreme ice conditions.

The antecedent heating term proves a useful index of ice potential in that it influences the date of ice formation and the extent of ice cover.

The formation, retention, and dissipation of ice cover, are directly affected by the depth of the lake, no doubt because the heat storage capacity of the water mass is proportional to its depth. In this connection, winds strong enough to produce waves, and thus compaction of the ice and mixing of the surface water with warmer water at depth, are a deterrent to ice growth. In deeper lakes this action substantially reduces ice cover.

Reduction of ice cover is a much more rapid process than the formation of ice, and requires a much smaller change in temperature. This melting takes place after only a few short periods of above-freezing daytime temperatures. It has been noted that the thawing process in the late winter and early spring is associated with increased incoming solar radiation, and with the release of latent heat of condensation in condensation on the ice surface. It has also been suggested by Bauer and Dutton [4] that a change in the albedo of the snow and ice at this time of year accelerates the melting process.

Figures 2 to 10 provide a graphical method of forecasting ice cover for each of the lakes given a long-range forecast of mean temperatures. These ice forecasts may be improved by subjective consideration of the antecedent heating. Multiple regression equations (1) to (5) improve the predictive value of the study by stating ice cover in terms of both freezing degree-days and antecedent heating. Results from both of these methods may be further modified by subjective consideration of other meteorological factors such as wind, radiation, evaporation, and condensation.

While four years of ice observations is too short a period to produce conclusive results, it is hoped that this study, plus continued aerial reconnaissance, more observations of the thickness and structural characteristics of lake ice, and increased attention to the fundamental physics of freezing and melting, will eventually lead to a better understanding of the meteorological aspects of ice cover on the Great Lakes.

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REFERENCES

1. D. C. Archibald, M. N. Monsinger, and T. B. Kilpatrick, "Aerial Ice Observing and Reconnaissance, the Great Lakes 1960," CIR 3361, TEC 328, Dept. of Transport, Meteorological Branch, Canada, 1960.
2. D. C. Archibald, M. N Monsinger, and T. B. Kilpatrick, "Aerial Ice Observing and Reconnaissance, the Great Lakes 1961," CIR 3530, TEC 371, Dept. of Transport, Meteorological Branch, Canada, 1961.
3. D. C. Archibald, M. N. Monsinger, and T. B. Kilpatrick, "Aerial Ice Observing and Reconnaissance, the Great Lakes 1962," CIR 3772, TEC 440, Dept. of Transport, Meteorological Branch, Canada, 1962.
4. K. G. Bauer and J. A. Dutton, "Albedo Variations Measured from an Airplane over Several Types of Surface," *Journal of Geophysical Research*, vol. 67, No. 6, June 1962, pp. 2367–2376.
5. F. E. Burbidge and J. R. Lauder, "A Preliminary Investigation into Freeze-Up and Break-Up Conditions in Canada," CIR 2939, TEC 252, Dept. of Transport, Meteorological Branch, Canada, 1957.
6. E. B. Callaway, "An Analysis of Environmental Factors Affecting Ice Growth," TR7, U.S. Navy Hydrographic Office, 1954.
7. V. V. Lebedev, "New Formulas on the Growth of Ice in Arctic Rivers and Seas," *Meteorologii͡a i Gidrologii͡a*, vol. 6, No. 8, 1940, pp. 40–51.
8. O. S. Lee and L. S. Simpson, "A Practical Method of Predicting Sea Ice Formation and Growth," TR4, U.S. Navy Hydrographic Office, 1954.
9. W. E. Markham, "Freezing and Melting Degree-Day Computations in Spring and Fall Months," CIR 3350, TEC 325, Dept. of Transport, Meteorological Branch, Canada, 1960.

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